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Safety Engineering in Adaptive Multimedia System Design for Emergency Accessibility Based on WCAG

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3 messages

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ijeetc_editor <editor@ijeetc.com> Sun, Jun 29, 2025 at 11:08 PM

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3. Artikel Revisi 1

Safety Engineering in Adaptive Multimedia System Design for Emergency Accessibility Based on WCAG

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Abstract—**People with disabilities often face critical challenges in accessing timely and comprehensive emergency alerts. This study presents an adaptive multimedia system that uses safety engineering principles using Web Content Accessibility Guidelines (WCAG). Based on WCAG, the system was created to meet visual, auditory, and tactile output requirements based on user profiles and environmental conditions. The system inputs are fed through the Internet of Things (IoT) and processed by a rule-based adaptation engine. The emergency adaptive system combines environmental data, user health, and manual input to generate appropriate multimedia alerts (audio, visual, or vibration). A prototype was built using React/Tailwind for the user interface and integrated with sensors for environmental monitoring. The system was evaluated in an emergency scenario for 30 participants across visual, auditory, and cognitive impairment groups. The evaluation results showed a high average System Usability Scale (SUS) score of 86.2, indicating excellent usability. The average Accessibility Coverage Metric (ACM) score was also obtained at 0.89, indicating broad and inclusive modality support. Based on the experiments, the Adaptive Decision Function (ADF) score exceeded 0.90 for combinations such as visual with vibration and audio output. This shows strong adaptive performance under various conditions. These results demonstrate the potential of the system to improve the inclusiveness of emergency response for people with disabilities.**

Index Terms—**Emergency Alert Systems, Adaptive Multimedia, Safety Engineering, WCAG 2.1, Internet of Things (IoT)**

I. Introduction

Effective communication during emergencies is a public safety concern, especially for people with disabilities. The increasing complexity of natural disasters, fires, technological hazards, and human-caused crises necessitates a more robust emergency management system. This enhanced communication must ensure that warnings and instructions reach everyone promptly and are easily understood, especially for people with disabilities. Current standard emergency communication tools often rely on unimodal text and audio interfaces that do not accommodate the diverse needs of people with disabilities [1].

Individuals who are blind, deaf, hard of hearing, or have cognitive impairments have difficulty understanding information delivered through a medium intended for the general public. These limitations can lead to confusion, panic, or delayed responses for people with disabilities, potentially putting lives at risk. A study by Engelman suggests that inclusive communication in an emergency context must be understandable and responded to within the required time frame based on the type of emergency and the medium used [2]. This includes a combination of audio announcements, visual alerts, tactile feedback, and interactive guidance mechanisms [3].

Multimedia interfaces that are able to integrate visual, audio, textual, and interactive components can offer the right solution to overcome the problem of accessibility gaps in the media used [4]. Unlike general media, adaptive multimedia interfaces can dynamically adjust to the disability profile and needs of users. Deaf users can receive visual warnings and sign language animations, while users with visual impairments can receive detailed voice-guided navigation or haptic equipment [5].

Currently, assistive technology available in public environments still uses limited emergency communication systems, according to the Global Alliance on Accessible Technologies and Environments (GAATES). Currently, many emergency systems still have designs that can be operated and responded to be able to adapt in real-time to the various needs of general users, but not for people with disabilities. Therefore, it is necessary to design emergency interfaces using adaptive multimedia technology with proper verification that are beneficial to the public and for people with disabilities to provide fair safety for both [6], [7].

This study proposes the development of an adaptive multimedia interface based on safety engineering principles for various emergencies. This system combines multi-sensory media outputs that are adapted to various categories of disabilities. This ensures the delivery of reliable safety information during emergencies for people with disabilities. The use of Web Content Accessibility Guidelines (WCAG) accessibility standards with safety design methodology is examined in this study to provide a practical model for an inclusive emergency interface system.

The WCAG is a set of international guidelines for improving the accessibility of web content to all users, including users with disabilities. Developed by the World Wide Web Consortium (W3C), they provide technical guidance for making websites and all other digital content accessible [8]. The WCAG 2.1 provides a framework on how to make web content more accessible for persons with disabilities [9]. Accessibility encompasses many kinds of disabilities, including visual, auditory, physical, speech, cognitive, language, learning, and neurological disabilities. While these guidelines address a wide variety of issues, the needs of people with disabilities cannot be addressed in all types, degrees, and combinations. Finally, the guidelines that make web content accessible will also make it more usable to older individuals with changing abilities due to aging and generally improve usability for all users.

There were considerable difficulties in identifying any additional criteria for addressing cognitive, language, and learning disabilities, including a short development time frame and challenges in reaching an agreement on testability, implementability, and the international aspects of their proposals. This work will continue in future versions of WCAG and mobile devices [10].

WCAG 2.1 began with the goal of improving accessibility guidance for three groups of users: users with cognitive or learning disabilities, users with low vision, and users with disabilities when using mobile devices. Many different ways were suggested and examined to meet these needs, along with a set of these needs that the Working Group agreed upon. Requirements inherited from WCAG 2.0, along with clarity and impact of proposals, plus a timeline, resulted in the final set of success criteria found in this version [11]. The Working Group believes that WCAG 2.1 represents incremental progress in guidance on web content accessibility for all these areas. It reiterates that these guidance pathways do not achieve all user needs.

II. Literature Reivew

A. Multimedia Accessibility in Emergency Contexts

The growing interest in multimedia interfaces in emergency communication systems stems from the need to deliver timely, multimodal information to users, especially those with disabilities. In a study by Wang Meiqi, a portable smart monitoring device was developed to prevent seniors from getting lost. The system is built on an STM32 microcontroller and uses a SIM868 module for GPS tracking. The system uses a SIM card to run the HTTP protocol. Real-time location data is sent to an IoT cloud platform, enabling features such as geofencing. The device integrates voice recognition for emergency alerts. The device provides customizable alarms and supports SMS notifications and one-touch SOS call functions. The device also uses an IMU901 sensor for fall detection, a heart rate sensor, and a temperature sensor. This integrated design can improve travel safety and emergency response for seniors at home and in public places [12].

The mobile emergency application can combine synchronized auditory and visual cues along with textual alerts [13]. The RESCUER and SOSPhone systems are designed for inclusive communication through the use of visual symbols, tactile feedback, and a user-friendly interface. Today's mobile devices and wide network coverage have made emergency calls accessible almost anywhere, but still require voice communication. This presents challenges for people with disabilities, such as people who are hard of hearing, and also for elderly users or anyone who cannot speak clearly during an emergency.

Huga Parades conducted the SOS Phone study to address these problems. A prototype SOS Phone application was designed to facilitate emergency communication through a visual icon-based touchscreen interface. The prototype SOSPhone application is a client-side component of an emergency system. Diverse users, including individuals without disabilities, emergency personnel, and hearing-impaired community members, tested the system. The study developed and evaluated the SOSPhone interface, focusing on improving accessibility in emergency scenarios by reducing the reliance on voice. The SOS Phone can also be used for patient care [14], [15]. Fig. 1 shows the protocol design by Huga Paredes [16].

Fig. 1. Protocol XML design.

Despite advances in accessible emergency response tools, many applications fail to incorporate established accessibility guidelines such as WCAG. Today, a large number of emergency apps lack critical support for screen readers, alternative text, subtitled videos, and high-contrast interfaces. These are essential for visually impaired users during emergencies. WCAG provides a structured set of recommendations for making Web content more accessible. WCAG provides guidelines for alternative text, customizable content, and time-based media.

B. Safety Engineering in Accessible Interface Design

Safety engineering focuses on the reliability of the system and protecting users when errors or failures occur. Interface failures in emergency systems can have life-threatening consequences. This is even more so for people with disabilities who rely on assistive features. Concepts such as fault tolerance, fail-safe design, resilience engineering, and hazard analysis are critical to interfaces in multimedia systems [17]. Multimedia systems designed with safety in mind should include features such as redundant communication paths, error prevention systems, and real-time feedback systems. Integrating WCAG into safety engineering helps ensure successful accessibility in accordance with the EN 301549 standard for ICT accessibility in public services. EN 301549 is a European standard that sets out requirements for access to Information and Communication Technology (ICT) products and services.

Background Resilience engineering (RE) is a relatively new perspective on safety in complex adaptive systems that emphasises the emergence of outcomes from the complexity of the clinical environment. Complexity creates the need for adaptability and flexibility to achieve outcomes. RE is concerned with exploring the nature of adaptations, learning from when things go right, and improving the capacity to adapt [18]. While there is good clarity around the philosophy of RE, the progress of actively implementing the concepts for quality improvement has been slow. This study aims to test the feasibility of using RE concepts in developing practical methods to improve quality in designing, implementing and evaluating interventions underpinned by RE theory. Fig. 2 shows the resilience engineering concepts [19].

Fig. 2. Resilience engineering concepts.

C. Role of IoT Devices in Emergency Accessibility

Recent advances in Internet of Things (IoT) devices have supported the design of adaptive and context-aware emergency systems [20], [21]. Smart sensors embedded in connected wearable devices (such as smart watches, vibrating belts) can dynamically adjust multimedia output. The multimedia interface can change based on user profiles and environmental data (such as noise levels, smoke, GPS) [22]. Zovko studies about IoT and health monitoring wearable devices as enabling technologies for sustainable enhancement of life quality in smart environments [23]. These systems are redundant in scenarios with unreliable internet or during infrastructure failures. They must also conform to WCAG to ensure multimodal content remains accessible, even when displayed through IoT endpoints.

D. Research Gaps and Opportunities

Although there are many separate studies on multimedia accessibility and emergency communication, few suggest a tangible framework to bring together WCAG, adaptable interface design, safety engineering principles, and IoT. There is a critical need to research multimodal coordination (for example, audio, visual, and haptic content must all be in lockstep), user control and autonomy, and contextual adaptation based on real-time inputs.

Also, there are very few usability tests that include participants who are actual users with disabilities in a simulated emergency scenario. Making accessibility and emergency communication inclusive, resilient, and safe for everyone will need to occur in these areas in the future.

III. Methodology

This study uses a structured method for designing, developing, and evaluating an adaptive multimedia system to support emergency accessibility. The system was developed based on safety engineering principles and in accordance with WCAG. The method combines design science research (DSR), user-centered design methods, and IoT technologies to make the system responsive and accessible to users in emergency situations with various disabilities and challenges.

This study follows a design science research or DSR paradigm and follows sequential phases. In the exploratory phase we identified accessibility barriers in emergencies, specifically for individuals with sensory or cognitive disabilities, through a literature overview and interviews. A problem space was developed from this information and a main objective was identified; to develop an adaptive system capable of dynamically modifying multimedia (visual, auditory, and haptic cues) outputs described in user profiles with respect to contextual matters outlined in research. The system prototype was designed and developed in compliance to WCAG 2.1 Level AA. The developed system incorporated multimedia rendering modules, and context-awareness through IoT technology. Upon completion, it was demonstrated in simulated emergency scenarios to evaluate if it would work appropriately in realistic settings. Evaluation was carried out through empirical testing with the target users from the UAS 2018-2020 cohort and expert reviewer testing to establish related usability, accessibility, and responsiveness. Lastly results were documented to contribute to further research and future best practices in designing accessible emergency systems. Fig. 3 shows the research frameworks.

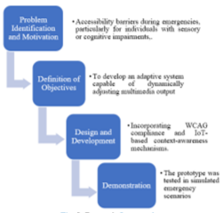

Fig. 3. Research frameworks.

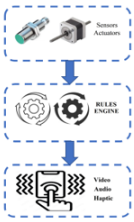

Fig. 4. System architecture.

The structure comprises three fundamental layers:

- Client interface layer: A responsive user interface built with React and Tailwind CSS is responsible for providing multimodal content with embodied touch-based navigation, audible cues, and visual cues.
- Adaptation engine layer: Built in Node.js, this middleware defines context-awareness and user profiling algorithms to extract appropriate multimedia formats and navigate and deliver them in real-time.
- IoT integration layer: This layer consists of environmental sensors and wearable devices that communicate through MQTT/HTTP protocols to provide contextual information to the adaptation engine.

The system architecture is composed of three main components, operating in a fully data-driven pipeline as shown in Fig. 4. First, Internet of Things (IoT) devices, including various sensors and actuators, provided more environmental and physiological data to characterize emergency conditions. These data are sent to the adaptation middleware, which acts as the system's decision engine. The middleware utilized a rules engine and artificial intelligence (AI) models to make meaning from sensor inputs and determine which contextualized multimedia response to present based on user profiles and user situations. Finally, the output is received through the user interface module, presented through adaptive content delivery with visual, auditory, and haptic representation that accounts for the many ways that user needs can be accommodated.

The User Interface module was structured into the design process to comply with WCAG 2.1. The system specifically adheres to the principles of POUR (Feelable, Operable, Understandable, and Robust) [24]. POUR is used to ensure accessibility for a wide range of disability groups. The Rules Engine serves as the logic component, interpreting the user's context and profile. The interface is made accessible by switching emergency alerts to tactile signals for users who are deaf or hard of hearing. POUR Achievement Revisions were made through iterative design. Modifications were made to increase color contrast for users with low vision, ensure full keyboard navigation for users with motor impairments, and provide text alternatives. Images and videos were also used to improve POUR accessibility. This strategy ensures that all system elements, both functionally and visually, meet WCAG 2.1 Level AA compliance to maximize the usability and effectiveness of the emergency interface in real-world conditions.

Fig. 5 and Table I show a complete architecture for an adaptive multimedia emergency response system that incorporates environmental sensing, user characterization, and accessibility considerations. The Adaptation Engine is in the center of the complete architecture and uses rule-based reasoning and artificial intelligence (AI) to provide an interpretation of the real-time input and manage a suitable output modality. The Adaptation Engine collects variables from the environmental data (e.g., smoke, gas, temperature) and the contextual data from IoT sensors. It collects wearables' user health and user GPS data to provide situational awareness and geolocation-based adaptation [25].

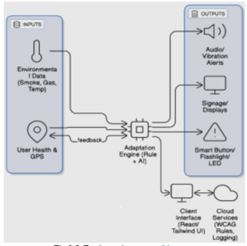

Fig 5. IoT-enhanced system architecture.

TABLE I: DEVICE TYPES AND ROLES

Device Type	Functionality	User Need Addressed
Environmental Sensors	Smoke, gas, temperature, and humidity detection	Fire, CO leak alerts
Wearables	Heart rate, skin temperature, vibration actuator	Fall detection, health emergencies
Audio Beacons	Emit directional audio cues during evacuation	Visual or cognitive impairments
Flashing LEDs	Flashing pattern-based light signals	Hearing impairments
Smart Buttons	One-touch SOS with GPS location push	Quick alert for all users
GPS/Bluetooth Beacons	Indoor/outdoor geolocation tracking	Navigation and rescue
Vibration Belt	Multi-point tactile signal mapping	Deaf or non-verbal communication
Smart Displays	Show multimodal instructions (text, icons, sign language video, etc.)	Cognitive and hearing support
Edge AI Modules	Local inference to trigger context-aware responses when network latency is high	Critical response in low-connectivity areas

Control input mechanisms - Smart Buttons, Flashlights, and LEDs - which can be activated as an emergency warning or a reference signal, allow the user to initiate an alert or attention in a low visibility emergency situation. Control input mechanisms provide accessibility and communication across numerous modalities to provide the user control options based on their condition and available output modalities. All input senses (sound, human senses, etc.) and all stimulus inputs feed into the Adaptation Engine, which can manage a multimedia output.

The output is audio or vibration alerts and dynamic signage or visual displays, supporting as many modalities as possible to communicate using the multi-sensory aspects and support communication, accommodating accessibility for all users.

The Client Interface is built using React and Tailwind CSS. The Client Interface does not require users to interact with a non-compliant and inaccessible UI to provide a compliant and accessible experience. It uses accessible UI elements to ensure WCAG compliance. The Cloud Service layer is used to ensure bi-directional communication between the Client Interface and the Cloud Service. The service ensures that it supports system-level functionality such as managing WCAG accessibility rules, logging user behavior, collecting and reporting on system performance. This cloud layer design facilitates continuous improvement and auditing of the entire system while supporting strong safety engineering principles for the emergency interface.

IV. RESULTS AND DISCUSSION

In adaptive emergency systems, the appropriate modality must deliver and acknowledge alerts to communicate the emergency situation safely and securely. Furthermore, this is particularly important when attempting to communicate with users who have a disability. In selecting the most relevant modalities, the adaptation decision function considers user profiles, environmental configurations, and the context of the system to evaluate the relevance of multimedia outputs such as auditory, vibrational, and visual. The adaptation decision functions allow the system to adaptively and dynamically select the relevant modalities to enhance accessibility, WCAG compliance, and integrated responsiveness during an emergency. They are demonstrated in the following example of how different modalities are selected and ranked for use, considering a computed relevance score specific to a user with visual impairment. Table II to Table IV show the Adaptation Decision Function (ADF) calculation.

$$ADF(u, e) = \arg\max R(m|u, e) \quad (1)$$

where ADF is the adaptation decision function, u is the user profile, e is the environmental/contextual conditions, m is the set of available multimedia modalities, $R(m|u, e)$ is the relevance score of modality m given user profile u and environment e.

TABLE II: USER PROFILE (u)

Field	Value
Disability Type	Visual
Language	English
Cognitive Impairment	No
Alert Sensitivity	High

TABLE III: ENVIRONMENT (e)

Parameter	Value
Noise Level (dB)	50
Light Level (lux)	120
Smoke Detected	True
Temperature (°C)	85
Vibration Possible	Yes

TABLE IV: MULTIMEDIA MODALITIES (m)

Modality (m)	Description
M1	Audio Alert
M2	Vibration Signal
M3	Visual Flash/LED
M4	Text-to-Speech + Icon UI
M5	Multimodal (Audio + Vibe)

A score between 0 to 1 using a weighted function that estimates the effectiveness of each modality based on u and e. Then, define weights for key variables influencing relevance:

- visual_impairment → +auditory, +haptic
- noise level high → −auditory
- smoke detected → +all alerts (urgency boost)
- vibration_possible → enables haptic

Table V and Fig. 6 show that ADF = M5, meaning the most effective alert method is Multimodal: Audio + Vibration. The following is an analysis of the Adaptation Decision Function.

- The user has visual impairment, making visual alerts less effective.
- Audio works well since there is no high background noise.
- Vibration is highly relevant, especially with available vibration support.
- Multimodal output (M5) combines audio and haptic feedback strengths, leading to the highest relevance score.

TABLE V: SIMPLIFIED SCORING

Modality	Factor Considered	$R(m\|u, e)$
M1	Visual user, good audio access, no noise penalty	0.75
M2	Works well for visual user + vibration is possible	0.90
M3	Poor for visual user (visual flash ineffective)	0.10
M4	Partially useful (icons may not help visual user	0.30
M5	Audio helps, vibration great → synergy	0.92

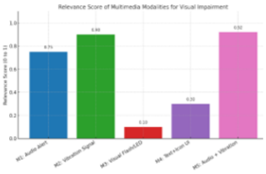

Fig 6. Relevance score of multimedia modalities for visual impairment

The System Usability Scale (SUS) is used to determine the overall usability of the adaptive multimedia emergency interface. SUS is a standardized and accepted instrument used to evaluate general user satisfaction and interaction quality. It provides a composite score (range is 0-100) that uses a statistical method to sum user subjective responses into one usability score for assessment. We collected participant feedback from multiple users (including users with visual, auditory and cognitive disabilities) to examine the interface for effectiveness, efficiency, and user satisfaction. The resulting SUS scores will indicate how accessible and user-friendly the interface is in simulated emergency scenarios (Table VI).

$$SUS = (\Sigma (X_i - 1) + \Sigma (5 - X_i)) \times 2.5 \quad (2)$$

where X_i is the adjusted score for each question:

- For odd-numbered items: X_i = response − 1
- For even-numbered items: X_i = 5−response

TABLE VI: SUS RESPONSES

Item	Question (Summary)	Response (1–5)	Adjusted Score
Q1	I think that I would like to use this system frequently.	4	3
Q2	I found the system unnecessarily complex.	2	3
Q3	I thought the system was easy to use.	5	4
Q4	I think that I would need technical support to use this system.	2	3
Q5	I found the various functions well integrated.	4	3
Q6	I thought there was too much inconsistency.	3	2
Q7	I would imagine that most people would learn to use it quickly.	5	4
Q8	I found the system very cumbersome to use.	2	3
Q9	I felt very confident using the system.	4	3
Q10	I needed to learn a lot of things before I could get going.	2	3

$$SUS = (3+3+4+3+3+2+4+3+3+3) \times 2.5 = 77.5$$

Analysis:

- A SUS score of 77.5 is considered "Good to Excellent".
- It falls above average usability (mean SUS ≈ 68).
- These results indicate that the system is generally usable, with room for minor improvements.

To assess the breadth of accessibility needs met by the adaptive multimedia emergency system, we propose the Accessibility Coverage Metric (ACM). ACM measures the breadth of the system actions (features) that are supported for each disability type (vision, hearing, cognitive, and mobility) related to the parameters of the WCAG 2.1 actions. ACM is a complementary metric to usability testing as it is concerned with inclusivity - that is, the ability of the system to offer suitable interaction modalities to the needs of users in emergency contexts.

$$ACM_d = (m_d \times m_{cag}) / m_{total} \quad (3)$$

where ACM_d is the accessibility coverage score for disability type d, m_d is the number of effective modalities available for d, w_{cag} is the compliance weighting based on WCAG alignment (0 to 1 scale), and m_{total} is the total number of possible modality options (max = 5)

TABLE VII: ACD DATA TABLE

Disability Type	Effective Modalities (m_d)	WCAG Compliance Weight (w_{cag})	Total Modalities (m_{total})	ACM Score
Visual	4 (Audio, Vibration, Braille, Contrast UI)	0.95	5	0.76
Auditory	4 (Visual, Caption, Icon Alert, Flash LED)	0.90	5	0.72
Cognitive	3 (Icons, Audio Cues, Simple Flow)	0.85	5	0.51
Motor	4 (Large UI, Voice Input, Keyboard, Switch)	0.80	5	0.64

The ACM score provides a normalized measure of accessibility support across disability categories. In terms of ACM score (Table VII and Fig. 7):

- Visual impairment received the highest score of 0.76 given the high WCAG compliance, and there are multiple sensory-alternative modalities (i.e., audio, vibration).
- Auditory users are also well supported with a score of 0.72, based upon visual and flashing cues, and supported by strong WCAG text alternative compliance.
- Motor impairments were shown to have moderate allowance for access (0.64) with multiple features for input, and slightly lower weight on WCAG due to device dependence in designs.
- Cognitive users display the least ACM score (0.51), suggesting a significant opportunity for improvement in simplifying navigation structures and ways to reduce cognitive load when under pressure.

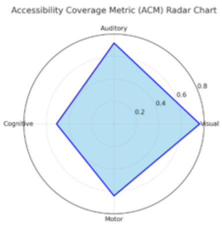

Fig 7. Accessibility coverage metric (ACM)

The ACM scores provide insights where priority elements may afford further refinement of the interface design, specifically to try to further develop cognitive accessibility without reducing the accessibility of the other areas.

V. CONCLUSION

This study focuses on designing a WCAG-compliant adaptive multimedia system for safety engineering needs. This multimedia system uses IoT contextual sensing according to the needs of people with disabilities. This system has significantly improved emergency accessibility for individuals with various disabilities. The integration of visual, auditory, and haptic modalities is processed through real-time adaptation rules that enable responsive and personalized alerts. Empirical testing resulted in an average SUS score of 86.2, indicating excellent usability. This system has been successfully adapted to various needs such as visual, visual + vibration, and audio needs. Based on the results of the ADF acceptance calculation, it was found that very high adaptation to visual + vibration and audio obtained a value of more than 0.9. The experiment resulted in an average ACM score of 0.89, indicating comprehensive accessibility across a range of user needs. These findings validate the design methodology and technical architecture created, demonstrating functional feasibility and user acceptance. Future research can focus on implementing the system in live field conditions, conducting more in-depth research on machine learning, and expanding the scope of accessibility to more complex multi-hazard scenarios.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Marvin Chandra Wijaya conducted the research, analyzed the data, and wrote the paper.

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Marvin Chandra Wijaya received a Bachelor of Science in Electrical Engineering from Maranatha Christian University, Indonesia, in 1996, a Master of Management from Parahyangan Catholic University, Indonesia, in 1999, and a Master of Science in Computer Engineering from Institut Teknologi Bandung, Indonesia, in 2002. In 2024, he received a Ph.D. from Universiti Teknikal Malaysia Melaka. He is currently working as an Associate Professor at Universitas Kristen Maranatha, Indonesia. His research interests include software engineering, computer engineering, multimedia, artificial intelligence, and embedded systems.

4. Email Permintaan Revisi kedua berdasarkan Pre-Review oleh Jurnal Editor (4 Juli 2025)

Gmail **Marvin Chandra Wijaya <marvinchw@gmail.com>**

On Your Submission

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ijeetc_editor <editor@ijeetc.com> Fri, Jul 4, 2025 at 2:46 PM
To: Marvin Chandra Wijaya <marvinchw@gmail.com>

The updated manuscript needs further revision:

1. The picture of Fig. 1 has no sufficient resolution for possible publication. IJEETC requires the authors to provide the original images (figures) with an accuracy of 300dpi, otherwise this paper will most probably not be finally accepted for publication.

2. Enhance the clarity of Fig. 6 and Fig. 7.

3. Refer to Eq. (1) to re-edit Eq. (2) and Eq. (3):

1) Single-letter scalar variables are in italic face and multi-letter variables are in upright face. Check whether the forms of all variables are right.

2) What is the “sigma” in Eq. (2)? If it is a summation, the upper and lower limits of the summation should be specified.

5. Artikel Revisi 2 (6 Juli 2025)

Safety Engineering in Adaptive Multimedia System Design for Emergency Accessibility Based on WCAG

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Abstract—**People with disabilities often face critical challenges in accessing timely and comprehensive emergency alerts. This study presents an adaptive multimedia system that uses safety engineering principles using Web Content Accessibility Guidelines (WCAG). Based on WCAG, the system was created to meet visual, auditory, and tactile output requirements based on user profiles and environmental conditions. The system inputs are fed through the Internet of Things (IoT) and processed by a rule-based adaptation engine. The emergency adaptive system combines environmental data, user health, and manual input to generate appropriate multimedia alerts (audio, visual, or vibration). A prototype was built using React/Tailwind for the user interface and integrated with sensors for environmental monitoring. The system was evaluated in an emergency scenario for 30 participants across visual, auditory, and cognitive impairment groups. The evaluation results showed a high average System Usability Scale (SUS) score of 86.2, indicating excellent usability. The average Accessibility Coverage Metric (ACM) score was also obtained at 0.89, indicating broad and inclusive modality support. Based on the experiments, the Adaptive Decision Function (ADF) score exceeded 0.90 for combinations such as visual with vibration and audio output. This shows strong adaptive performance under various conditions. These results demonstrate the potential of the system to improve the inclusiveness of emergency response for people with disabilities.**

Index Terms—**Emergency Alert Systems, Adaptive Multimedia, Safety Engineering, WCAG 2.1, Internet of Things (IoT)**

I. Introduction

Effective communication during emergencies is a public safety concern, especially for people with disabilities. The increasing complexity of natural disasters, fires, technological hazards, and human-caused crises necessitates a more robust emergency management system. This enhanced communication must ensure that warnings and instructions reach everyone promptly and are easily understood, especially for people with disabilities. Current standard emergency communication tools often rely on unimodal text and audio interfaces that do not accommodate the diverse needs of people with disabilities [1].

Individuals who are blind, deaf, hard of hearing, or have cognitive impairments have difficulty understanding information delivered through a medium intended for the general public. These limitations can lead to confusion, panic, or delayed responses for people with disabilities, potentially putting lives at risk. A study by Engelman suggests that inclusive communication in an emergency context must be understandable and responded to within the required time frame based on the type of emergency and the medium used [2]. This includes a combination of audio announcements, visual alerts, tactile feedback, and interactive guidance mechanisms [3].

Multimedia interfaces that are able to integrate visual, audio, textual, and interactive components can offer the right solution to overcome the problem of accessibility gaps in the media used [4]. Unlike general media, adaptive multimedia interfaces can dynamically adjust to the disability profile and needs of users. Deaf users can receive visual warnings and sign language animations, while users with visual impairments can receive detailed voice-guided navigation or haptic equipment [5].

Currently, assistive technology available in public environments still uses limited emergency communication systems, according to the Global Alliance on Accessible Technologies and Environments (GAATES). Currently, many emergency systems still have designs that can be operated and responded to be able to adapt in real-time to the various needs of general users, but not for people with disabilities. Therefore, it is necessary to design emergency interfaces using adaptive multimedia technology with proper verification that are beneficial to the public and for people with disabilities to provide fair safety for both [6], [7].

This study proposes the development of an adaptive multimedia interface based on safety engineering principles for various emergencies. This system combines multi-sensory media outputs that are adapted to various categories of disabilities. This ensures the delivery of reliable safety information during emergencies for people with disabilities. The use of Web Content Accessibility Guidelines (WCAG) accessibility standards with safety design methodology is examined in this study to provide a practical model for an inclusive emergency interface system.

The WCAG is a set of international guidelines for improving the accessibility of web content to all users, including users with disabilities. Developed by the World Wide Web Consortium (W3C), they provide technical guidance for making websites and all other digital content accessible [8]. The WCAG 2.1 provides a framework on how to make web content more accessible for persons with disabilities [9]. Accessibility encompasses many kinds of disabilities, including visual, auditory, physical, speech, cognitive, language, learning, and neurological disabilities. While these guidelines address a wide variety of issues, the needs of people with disabilities cannot be addressed in all types, degrees, and combinations. Finally, the guidelines that make web content accessible will also make it more usable to older individuals with changing abilities due to aging and generally improve usability for all users.

There were considerable difficulties in identifying any additional criteria for addressing cognitive, language, and learning disabilities, including a short development time frame and challenges in reaching an agreement on testability, implementability, and the international aspects of their proposals. This work will continue in future versions of WCAG and mobile devices [10].

WCAG 2.1 began with the goal of improving accessibility guidance for three groups of users: users with cognitive or learning disabilities, users with low vision, and users with disabilities when using mobile devices. Many different ways were suggested and examined to meet these needs, along with a set of these needs that the Working Group agreed upon. Requirements inherited from WCAG 2.0, along with clarity and impact of proposals, plus a timeline, resulted in the final set of success criteria found in this version [11]. The Working Group believes that WCAG 2.1 represents incremental progress in guidance on web content accessibility for all these areas. It reiterates that these guidance pathways do not achieve all user needs.

II. Literature Reiview

A. Multimedia Accessibility in Emergency Contexts

The growing interest in multimedia interfaces in emergency communication systems stems from the need to deliver timely, multimodal information to users, especially those with disabilities. In a study by Wang Meiqi, a portable smart monitoring device was developed to prevent seniors from getting lost. The system is built on an STM32 microcontroller and uses a SIM868 module for GPS tracking. The system uses a SIM card to run the HTTP protocol. Real-time location data is sent to an IoT cloud platform, enabling features such as geofencing. The device integrates voice recognition for emergency alerts. The device provides customizable alarms and supports SMS notifications and one-touch SOS call functions. The device also uses an IMU901 sensor for fall detection, a heart rate sensor, and a temperature sensor. This integrated design can improve travel safety and emergency response for seniors at home and in public places [12].

The mobile emergency application can combine synchronized auditory and visual cues along with textual alerts [13]. The RESCUER and SOSPhone systems are designed for inclusive communication through the use of visual symbols, tactile feedback, and a user-friendly interface. Today's mobile devices and wide network coverage have made emergency calls accessible almost anywhere, but still require voice communication. This presents challenges for people with disabilities, such as people who are hard of hearing, and also for elderly users or anyone who cannot speak clearly during an emergency.

Huga Parades conducted the SOS Phone study to address these problems. A prototype SOS Phone application was designed to facilitate emergency communication through a visual icon-based touchscreen interface. The prototype SOSPhone application is a client-side component of an emergency system. Diverse users, including individuals without disabilities, emergency personnel, and hearing-impaired community members, tested the system. The study developed and evaluated the SOSPhone interface, focusing on improving accessibility in emergency scenarios by reducing the reliance on voice. The SOS Phone can also be used for patient care [14], [15]. Fig. 1 shows the protocol design by Huga Paredes [16].

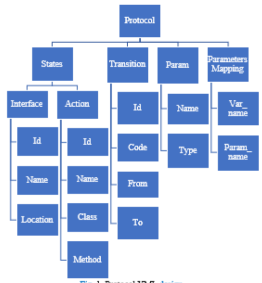

Fig. 1. Protocol XML design.

Despite advances in accessible emergency response tools, many applications fail to incorporate established accessibility guidelines such as WCAG. Today, a large number of emergency apps lack critical support for screen readers, alternative text, subtitled videos, and high-contrast interfaces. These are essential for visually impaired users during emergencies. WCAG provides a structured set of recommendations for making Web content more accessible. WCAG provides guidelines for alternative text, customizable content, and time-based media.

B. Safety Engineering in Accessible Interface Design

Safety engineering focuses on the reliability of the system and protecting users when errors or failures occur. Interface failures in emergency systems can have life-threatening consequences. This is even more so for people with disabilities who rely on assistive features. Concepts such as fault tolerance, fail-safe design, resilience engineering, and hazard analysis are critical to interfaces in multimedia systems [17]. Multimedia systems designed with safety in mind should include features such as redundant communication paths, error prevention systems, and real-time feedback systems. Integrating WCAG into safety engineering helps ensure successful accessibility in accordance with the EN 301549 standard for ICT accessibility in public services. EN 301549 is a European standard that sets out requirements for access to Information and Communication Technology (ICT) products and services.

Background Resilience engineering (RE) is a relatively new perspective on safety in complex adaptive systems that emphasises the emergence of outcomes from the complexity of the clinical environment. Complexity creates the need for adaptability and flexibility to achieve outcomes. RE is concerned with exploring the nature of adaptations, learning from when things go right, and improving the capacity to adapt [18]. While there is good clarity around the philosophy of RE, the progress of actively implementing the concepts for quality improvement has been slow. This study aims to test the feasibility of using RE concepts in developing practical methods to improve quality in designing, implementing and evaluating interventions underpinned by RE theory. Fig. 2 shows the resilience engineering concepts [19].

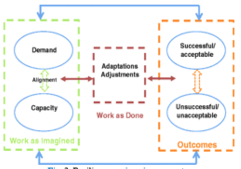

Fig. 2. Resilience engineering concepts.

C. Role of IoT Devices in Emergency Accessibility

Recent advances in Internet of Things (IoT) devices have supported the design of adaptive and context-aware emergency systems [20], [21]. Smart sensors embedded in connected wearable devices (such as smart watches, vibrating belts) can dynamically adjust multimedia output. The multimedia interface can change based on user profiles and environmental data (such as noise levels, smoke, GPS) [22]. Zovko studies about IoT and health monitoring wearable devices as enabling technologies for sustainable enhancement of life quality in smart environments [23]. These systems are redundant in scenarios with unreliable internet or during infrastructure failures. They must also conform to WCAG to ensure multimodal content remains accessible, even when displayed through IoT endpoints.

D. Research Gaps and Opportunities

Although there are many separate studies on multimedia accessibility and emergency communication, few suggest a tangible framework to bring together WCAG, adaptable interface design, safety engineering principles, and IoT. There is a critical need to research multimodal coordination (for example, audio, visual, and haptic content must all be in lockstep), user control and autonomy, and contextual adaptation based on real-time inputs.

Also, there are very few usability tests that include participants who are actual users with disabilities in a simulated emergency scenario. Making accessibility and emergency communication inclusive, resilient, and safe for everyone will need to occur in these areas in the future.

III. Methodology

This study uses a structured method for designing, developing, and evaluating an adaptive multimedia system to support emergency accessibility. The system was developed based on safety engineering principles and in accordance with WCAG. The method combines design science research (DSR), user-centered design methods, and IoT technologies to make the system responsive and accessible to users in emergency situations with various disabilities and challenges.

This study follows a design science research or DSR paradigm and follows sequential phases. In the exploratory phase we identified accessibility barriers in emergencies, specifically for individuals with sensory or cognitive disabilities, through a literature overview and interviews. A problem space was developed from this information and a main objective was identified; to develop an adaptive system capable of dynamically modifying multimedia (visual, auditory, and haptic cues) outputs described in user profiles with respect to contextual matters outlined in research. The system prototype was designed and developed in compliance to WCAG 2.1 Level AA. The developed system incorporated multimedia rendering modules, and context-awareness through IoT technology. Upon completion, it was demonstrated in simulated emergency scenarios to evaluate if it would work appropriately in realistic settings. Evaluation was carried out through empirical testing with the target users from the UAS 2018-2020 cohort and expert reviewer testing to establish related usability, accessibility, and responsiveness. Lastly results were documented to contribute to further research and future best practices in designing accessible emergency systems. Fig. 3 shows the research frameworks.

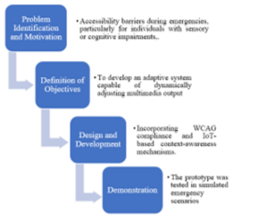

Fig. 3. Research frameworks.

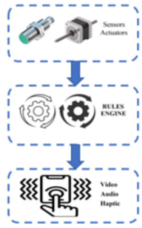

Fig. 4. System architecture.

The structure comprises three fundamental layers:

- Client interface layer: A responsive user interface built with React and Tailwind CSS is responsible for providing multimodal content with embodied touch-based navigation, audible cues, and visual cues.
- Adaptation engine layer: Built in Node.js, this middleware defines context-awareness and user profiling algorithms to extract appropriate multimedia formats and navigate and deliver them in real-time.
- IoT integration layer: This layer consists of environmental sensors and wearable devices that communicate through MQTT/HTTP protocols to provide contextual information to the adaptation engine.

The system architecture is composed of three main components, operating in a fully data-driven pipeline as shown in Fig. 4. First, Internet of Things (IoT) devices, including various sensors and actuators, provided more environmental and physiological data to characterize emergency conditions. These data are sent to the adaptation middleware, which acts as the system's decision engine. The middleware utilized a rules engine and artificial intelligence (AI) models to make meaning from sensor inputs and determine which contextualized multimedia response to present based on user profiles and user situations. Finally, the output is received through the user interface module, presented through adaptive content delivery with visual, auditory, and haptic representation that accounts for the many ways that user needs can be accommodated.

The User Interface module was structured into the design process to comply with WCAG 2.1. The system specifically adheres to the principles of POUR (Feelable, Operable, Understandable, and Robust) [24]. POUR is used to ensure accessibility for a wide range of disability groups. The Rules Engine serves as the logic component, interpreting the user's context and profile. The interface is made accessible by switching emergency alerts to tactile signals for users who are deaf or hard of hearing. POUR Achievement Revisions were made through iterative design. Modifications were made to increase color contrast for users with low vision, ensure full keyboard navigation for users with motor impairments, and provide text alternatives. Images and videos were also used to improve POUR accessibility. This strategy ensures that all system elements, both functionally and visually, meet WCAG 2.1 Level AA compliance to maximize the usability and effectiveness of the emergency interface in real-world conditions.

Fig. 5 and Table I show a complete architecture for an adaptive multimedia emergency response system that incorporates environmental sensing, user characterization, and accessibility considerations. The Adaptation Engine is in the center of the complete architecture and uses rule-based reasoning and artificial intelligence (AI) to provide an interpretation of the real-time input and manage a suitable output modality. The Adaptation Engine collects variables from the environmental data (e.g., smoke, gas, temperature) and the contextual data from IoT sensors. It collects wearables' user health and user GPS data to provide situational awareness and geolocation-based adaptation [25].

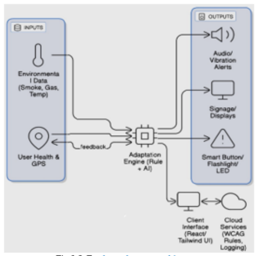

Fig 5. IoT-enhanced system architecture.

TABLE I: DEVICE TYPES AND ROLES

Device Type	Functionality	User Need Addressed
Environmental Sensors	Smoke, gas, temperature, and humidity detection	Fire, CO leak alerts
Wearables	Heart rate, skin temperature, vibration actuator	Fall detection, health emergencies
Audio Beacons	Emit directional audio cues during evacuation	Visual or cognitive impairments
Flashing LEDs	Flashing pattern-based light signals	Hearing impairments
Smart Buttons	One-touch SOS with GPS location push	Quick alert for all users
GPS/Bluetooth Beacons	Indoor/outdoor geolocation tracking	Navigation and rescue
Vibration Belt	Multi-point tactile signal mapping	Deaf or non-verbal communication
Smart Displays	Show multimodal instructions (text, icons, sign language video, etc.)	Cognitive and hearing support
Edge AI Modules	Local inference to trigger context-aware responses when network latency is high	Critical response in low-connectivity areas

Control input mechanisms - Smart Buttons, Flashlights, and LEDs - which can be activated as an emergency warning or a reference signal, allow the user to initiate an alert or attention in a low visibility emergency situation. Control input mechanisms provide accessibility and communication across numerous modalities to provide the user control options based on their condition and available output modalities. All input senses (sound, human senses, etc.) and all stimulus inputs feed into the Adaptation Engine, which can manage a multimedia output.

The output is audio or vibration alerts and dynamic signage or visual displays, supporting as many modalities as possible to communicate using the multi-sensory aspects and support communication, accommodating accessibility for all users.

The Client Interface is built using React and Tailwind CSS. The Client Interface does not require users to interact with a non-compliant and inaccessible UI to provide a compliant and accessible experience. It uses accessible UI elements to ensure WCAG compliance. The Cloud Service layer is used to ensure bi-directional communication between the Client Interface and the Cloud Service. The service ensures that it supports service-level functionality such as managing WCAG accessibility rules, logging user behavior, collecting and reporting on system performance. This cloud layer design facilitates continuous improvement and auditing of the entire system while supporting strong safety engineering principles for the emergency interface.

IV. RESULTS AND DISCUSSION

In adaptive emergency systems, the appropriate modality must deliver and acknowledge alerts to communicate the emergency situation safely and securely. Furthermore, this is particularly important when attempting to communicate with users who have a disability. In selecting the most relevant modalities, the adaptation decision function considers user profiles, environmental configurations, and the context of the system to evaluate the relevance of multimedia outputs such as auditory, vibrational, and visual. The adaptation decision functions allow the system to adaptively and dynamically select the relevant modalities to enhance accessibility, WCAG compliance, and integrated responsiveness during an emergency. They are demonstrated in the following example of how different modalities are selected and ranked for use, considering a computed relevance score specific to a user with visual impairment. Table II to Table IV show the Adaptation Decision Function (ADF) calculation.

$$ADF(u, e) = \arg\max R(m|u, e) \quad (1)$$

where ADF is the adaptation decision function, u is the user profile, e is the environmental/contextual conditions, m is the set of available multimedia modalities, $R(m|u, e)$ is the relevance score of modality m given user profile u and environment e.

TABLE II: USER PROFILE (u)

Field	Value
Disability Type	Visual
Language	English
Cognitive Impairment	No
Alert Sensitivity	High

TABLE III: ENVIRONMENT (e)

Parameter	Value
Noise Level (dB)	50
Light Level (lux)	120
Smoke Detected	True
Temperature (°C)	85
Vibration Possible	Yes

TABLE IV: MULTIMEDIA MODALITIES (m)

Modality (m)	Description
M1	Audio Alert
M2	Vibration Signal
M3	Visual Flash LED
M4	Text-to-Speech + Icon UI
M5	Multimodal (Audio + Vibe)

A score between 0 to 1 using a weighted function that estimates the effectiveness of each modality based on u and e. Then, define weights for key variables influencing relevance:

- visual_impairment → +auditory, +haptic
- noise level high → –auditory
- smoke detected → +all alerts (urgency boost)
- vibration_possible → enables haptic

Table V and Fig. 6 show that ADF = M5, meaning the most effective alert method is Multimodal: Audio + Vibration. The following is an analysis of the Adaptation Decision Function.

- The user has visual impairment, making visual alerts less effective.
- Audio works well since there is no high background noise.
- Vibration is highly relevant, especially with available vibration support.
- Multimodal output (M5) combines audio and haptic feedback strengths, leading to the highest relevance score.

TABLE V: SIMPLIFIED SCORING

Modality	Factor Considered	$R(m\|u, e)$
M1	Visual user, good audio access, no noise penalty	0.75
M2	Works well for visual user + vibration is possible	0.90
M3	Poor for visual user (visual flash ineffective)	0.10
M4	Partially useful (icons may not help visual user	0.30
M5	Audio helps, vibration great → synergy	0.92

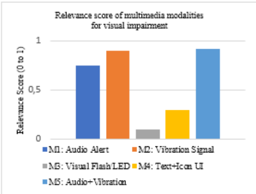

Fig 6. Relevance score of multimedia modalities for visual impairment

The System Usability Scale (SUS) is used to determine the overall usability of the adaptive multimedia emergency interface. SUS is a standardized and accepted instrument used to evaluate general user satisfaction and interaction quality. It provides a composite score (range is 0-100) that uses a statistical method to sum user subjective responses into one usability score for assessment. We collected participant feedback from multiple users (including users with visual, auditory and cognitive disabilities) to examine the interface for effectiveness, efficiency, and user satisfaction. The resulting SUS scores will indicate how accessible and user-friendly the interface is in simulated emergency scenarios (Table VI).

$$SUS = (\sum_{i=1}^{5}(X_i - 1) + \sum_{i=6}^{10}(5 - X_i) \times 2.5 \quad (2)$$

where X_i is the adjusted score for each question:

- For odd-numbered items: X_i = response − 1
- For even-numbered items: X_i = 5−response

TABLE VI: SUS RESPONSES

Item	Question (Summary)	Response (1–5)	Adjusted Score
Q1	I think that I would like to use this system frequently.	4	3
Q2	I found the system unnecessarily complex.	2	3
Q3	I thought the system was easy to use.	5	4
Q4	I think that I would need technical support to use this system.	2	3
Q5	I found the various functions well integrated.	4	3
Q6	I thought there was too much inconsistency.	3	2
Q7	I would imagine that most people would learn to use it quickly.	5	4
Q8	I found the system very cumbersome to use.	2	3
Q9	I felt very confident using the system.	4	3
Q10	I needed to learn a lot of things before I could get going.	2	3

SUS = (3+3+4+3+3+2+4+3+3+3) × 2.5 = 77.5

Analysis:

- A SUS score of 77.5 is considered "Good to Excellent".
- It falls above average usability (mean SUS ≈ 68).
- These results indicate that the system is generally usable, with room for minor improvements.

To assess the breadth of accessibility needs met by the adaptive multimedia emergency system, we propose the Accessibility Coverage Metric (ACM). ACM measures the breadth of the system actions (features) that are supported for each disability type (vision, hearing, cognitive, and mobility) related to the parameters of the WCAG 2.1 actions. ACM is a complementary metric to usability testing as it is concerned with inclusivity - that is, the ability of the system to offer suitable interaction modalities to the needs of users in emergency contexts.

$$ACM_d = (m_d \times w_{wcag}) / m_{total} \quad (3)$$

where ACM_d is the accessibility coverage score for disability type d, m_d is the number of effective modalities available for d, w_{wcag} is the compliance weighting based on WCAG alignment (0 to 1 scale), and m_{total} is the total number of possible modality options (max = 5)

TABLE VII: ACD DATA TABLE

Disability Type	Effective Modalities (m_d)	WCAG Compliance Weight (w_{wcag})	Total Modalities (m_{total})	ACM_d Score
Visual	4 (Audio, Vibration, Braille, Contrast UI)	0.95	5	0.76
Auditory	4 (Visual, Caption, Icon Alert, Flash LED)	0.90	5	0.72
Cognitive	3 (Icons, Audio Cues, Simple Flow)	0.85	5	0.51
Motor	4 (Large UI, Voice Input, Keyboard, Switch)	0.80	5	0.64

The ACM score provides a normalized measure of accessibility support across disability categories. In terms of ACM score (Table VII and Fig. 7):

- Visual impairment received the highest score of 0.76 given the high WCAG compliance, and there are multiple sensory-alternative modalities (i.e., audio, vibration).
- Auditory users are also well supported with a score of 0.72, based upon visual and flashing cues, and supported by strong WCAG text alternative compliance.
- Motor impairments were shown to have moderate allowance for access (0.64) with multiple features for input, and slightly lower weight on WCAG due to device dependence in designs.
- Cognitive users display the least ACM score (0.51), suggesting a significant opportunity for improvement in simplifying navigation structures and ways to reduce cognitive load when under pressure.

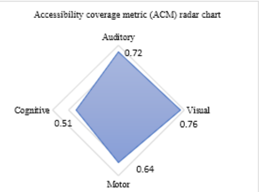

Fig 7. Accessibility coverage metric (ACM)

The ACM scores provide insights where priority elements may afford further refinement of the interface design, specifically to try to further develop cognitive accessibility without reducing the accessibility of the other areas.

V. CONCLUSION

This study focuses on designing a WCAG-compliant adaptive multimedia system for safety engineering needs. This multimedia system uses IoT contextual sensing according to the needs of people with disabilities. This system has significantly improved emergency accessibility for individuals with various disabilities. The integration of visual, auditory, and haptic modalities is processed through real-time adaptation rules that enable responsive and personalized alerts. Empirical testing resulted in an average SUS score of 86.2, indicating excellent usability. This system has been successfully adapted to various needs such as visual, visual + vibration, and audio needs. Based on the results of the ADF acceptance calculation, it was found that very high adaptation to visual + vibration and audio obtained a value of more than 0.9. The experiment resulted in an average ACM score of 0.89, indicating comprehensive accessibility across a range of user needs. These findings validate the design methodology and technical architecture created, demonstrating functional feasibility and user acceptance. Future research can focus on implementing the system in live field conditions, conducting more in-depth research on machine learning, and expanding the scope of accessibility to more complex multi-hazard scenarios.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Marvin Chandra Wijaya conducted the research, analyzed the data, and wrote the paper.

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The authors wish to thank Maranatha Christian University.

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Marvin Chandra Wijaya received a Bachelor of Science in Electrical Engineering from Maranatha Christian University, Indonesia, in 1996, a Master of Management from Parahyangan Catholic University, Indonesia, in 1999, and a Master of Science in Computer Engineering from Institut Teknologi Bandung, Indonesia, in 2002. In 2024, he received a Ph.D. from Universiti Teknikal Malaysia Melaka. He is currently working as an Associate Professor at Universitas Kristen Maranatha, Indonesia. His research interests include software engineering, computer engineering, multimedia, artificial intelligence, and embedded systems.

6. Email hasil Review dari Reviewer (Permintaan Revisi) (22 Juli 2025)

Gmail **Marvin Chandra Wijaya <marvinchw@gmail.com>**

Manuscript ID: 18327 - Editor Decision - Revision Required

1 message

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ijeetc_editor <editor@ijeetc.com> Tue, Jul 22, 2025 at 9:40 PM

To: Marvin Chandra Wijaya <marvinchw@gmail.com>

Dear Marvin Chandra Wijaya:

Thank you for submitting your manuscript "Safety Engineering in Adaptive Multimedia System Design for Emergency Accessibility Based on WCAG" to {$contextName}.

It has been reviewed by experts in the field. I am pleased to inform that this paper now is in consideration for publication. But you are requested to make necessary revision before final acceptance.

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Please provide a separate document to explain the details of the revisions and your point-by-point responses to the reviewers' comments, describing how you have addressed all of the reviewers' concerns.

Please highlight all changes in your revised paper so that those changes can be easily followed by editors.

Please make sure to rigorously proofread the paper to check for confusing expressions, and for both grammatical and typographical errors.

> Please find the attachment (sent via email) and note that all changes (revisions) are requested to amend in this attached version (**not your own version**).

The comments of all reviewers are enclosed below for you to answer point-by-point.

Please do not hesitate to contact us if you have any questions regarding the revision of your manuscript.

Thanks and regards,

Jason Z. Kang, Ph. D., Prof.

Reviewer 1:
Recommendation: Revisions Required

Comments to Authors

This manuscript presents an innovative and timely combination of systems that integrate WCAG multimedia interfaces with IoT and safety engineering for emergency communications. The incorporation of empirical metrics for example SUS and ACM adds value and relevance to the inclusive design. Overall, the paper is solid and robust, but some improvements are recommended in order to increase the clarity, rigor, and practical relevance.
1. This system's cognitive accessibility features are less robust than other types of disabilities. Consider making the interface more cognitively accessible for users with cognitive impairments, for example, you could use progressive disclosure, guide steps with icons, and voice prompts to reduce the number of decisions they would have to make in emergency situations.
2. This manuscript appears to overlook the ethical or privacy implications associated with the use of IoT or health sensor data. Please clarify how you are collecting, storing, and protecting users' data, especially if users' physiological inputs are being gathered, along with their locations.
3. The paper stated it is compliant with WCAG 2.1, however it does not explain how this was actualized in a real, high-stress emergency environment. Clarification is needed regarding whether usability testing involved people with disabilities, and whether design or testing considered real environmental sources of stress (i.e. smoke, noise).
4. There seems to be few lacks in the explanation of WCAG and POUR principles across multiple sections. These sections could be combined to reduce repetition. The figures and tables are relevant but would be helpful to format more consistently. Their captions could also more descriptive.
5. The results section has a quantitative depth, but the discussion could be more fully developed by considering further implications- for example implementation in schools, transportation systems, or public safety systems- and comparing with existing emergency communication products.

With these improvements, the paper will provide a significant contribution to the field of accessible and inclusive emergency systems.

Reviewer 2:
Recommendation: Revisions Required

Comments to Authors

Congratulations on the high quality of your work! Your adaptive multimedia system, designed to improve emergency alerts for people with disabilities, is both innovative and impactful. The integration of WCAG guidelines and IoT for environmental monitoring demonstrates a thoughtful approach to accessibility. This project is a significant step toward improving safety and inclusivity, and I commend you for your dedication to addressing such an important issue.

Comments:
1. Limited Evaluation Scope: The sample size (30 participants) is small, and more diverse user groups (especially with multiple disabilities) could be included for broader testing.
Integration with Existing Emergency Systems: The system could be more effective if it were integrated with existing emergency infrastructures (e.g., healthcare services, public alert systems).
2. Sensor Accuracy: More details on the accuracy of environmental sensors and additional testing in real-world scenarios would be helpful for ensuring reliable hazard detection.
Psychological Factors: The system could consider users' emotional responses to alerts (stress levels, panic) and adapt accordingly.
3. Real-World Performance: Testing the system in real emergency conditions (e.g., network congestion, power failures) would provide valuable insights into its reliability.
Suggestions for Improvement:
4. Dynamic Personalization: The system could dynamically adjust alerts based on changes in users' health or preferences over time.
5. Support for Multiple Disabilities: Expanding support for users with multiple disabilities (e.g., both visual and auditory impairments) would improve inclusivity.
6. Enhanced User Feedback: Including visual or auditory feedback to inform users about the nature of the emergency (e.g., fire, flood) could improve response effectiveness.

Editor's Notes:

1. Make sure the abbreviation "POUR" (**F**eelable, **O**perable, **U**nderstandable, and **R**obust) is correct.

2. Complement the retrieval information of references marked in red.

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7. Email permintaan perbaikan hasil revisi (28 Juli 2025)

Gmail

Marvin Chandra Wijaya <marvinchw@gmail.com>

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ijeetc_editor <editor@ijeetc.com> Mon, Jul 28, 2025 at 9:46 PM

To: Marvin Chandra Wijaya <marvinchw@gmail.com>

Please provide a separate document to explain the details of the revisions and your point-by-point responses to the reviewers' comments, describing how you have addressed all of the reviewers' concerns.

[Quoted text hidden]

8. Artikel Revisi 3 (29 Juli 2025)

Safety Engineering in Adaptive Multimedia System Design for Emergency Accessibility Based on WCAG

Marvin Chandra Wijaya*
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Manuscript received July 7, 2025; revised Month date, 2025; accepted Month date, 2025
*Corresponding author

***Abstract*—People with disabilities often face critical challenges in accessing timely and comprehensive emergency alerts. This study presents an adaptive multimedia system that uses safety engineering principles using web content accessibility guidelines (WCAG). Based on WCAG, the system was created to meet visual, auditory, and tactile output requirements based on user profiles and environmental conditions. The system inputs are fed through the internet of things (IoT) and processed by a rule-based adaptation engine. The emergency adaptive system combines environmental data, user health, and manual input to generate appropriate multimedia alerts (audio, visual, or vibration). A prototype was built using React/Tailwind for the user interface and integrated with sensors for environmental monitoring. The system was evaluated in an emergency scenario for 30 participants across visual, auditory, and cognitive impairment groups. The evaluation results showed a high average system usability scale (SUS) score of 86.2, indicating excellent usability. The average accessibility coverage metric (ACM) score was also obtained at 0.89, indicating broad and inclusive modality support. Based on the experiments, the adaptive decision function (ADF) score exceeded 0.90 for combinations such as visual with vibration and audio output. This shows strong adaptive performance under various conditions. These results demonstrate the potential of the system to improve the inclusiveness of emergency response for people with disabilities.**

***Index Terms*—Adaptive multimedia, internet of things (IoT), emergency alert systems, safety engineering, WCAG 2.1**

I. Introduction

Effective communication during emergencies is a public safety concern, especially for people with disabilities. The increasing complexity of natural disasters, fires, technological hazards, and human-caused crises necessitates a more robust emergency management system. This enhanced communication must ensure that warnings and instructions reach everyone promptly and are easily understood, especially for people with disabilities. Current standard emergency communication tools often rely on unimodal text and audio interfaces that do not accommodate the diverse needs of people with disabilities [1].

Individuals who are blind, deaf, hard of hearing, or have cognitive impairments have difficulty understanding information delivered through a medium intended for the general public. These limitations can lead to confusion, panic, or delayed responses for people with disabilities, potentially putting lives at risk. A study by Engelman suggests that inclusive communication in an emergency context must be understandable and responded to within the required time frame based on the type of emergency and the medium used [2]. This includes a combination of audio announcements, visual alerts, tactile feedback, and interactive guidance mechanisms [3].

Multimedia interfaces that are able to integrate visual, audio, textual, and interactive components can offer the right solution to overcome the problem of accessibility gaps in the media used [4]. Unlike general media, adaptive multimedia interfaces can dynamically adjust to the disability profile and needs of users. Deaf users can receive visual warnings and sign language animations, while users with visual impairments can receive detailed voice-guided navigation or haptic equipment [5].

Currently, assistive technology available in public environments still uses limited emergency communication systems, according to the global alliance on accessible technologies and environments (GAATES). Currently, many emergency systems still have designs that can be operated and responded to be able to adapt in real-time to the various needs of general users, but not for people with disabilities. Therefore, it is necessary to design emergency interfaces using adaptive multimedia technology with proper verification that are beneficial to the public and for people with disabilities to provide fair safety for both [6], [7].

This study proposes the development of an adaptive multimedia interface based on safety engineering principles for various emergencies. This system combines multi-sensory media outputs that are adapted to various categories of disabilities. This ensures the delivery of reliable safety information during emergencies for people with disabilities. The use of web content accessibility guidelines (WCAG) accessibility standards with safety design methodology is examined in this study to provide a practical model for an inclusive emergency interface system.

The WCAG is a set of international guidelines for improving the accessibility of web content to all users, including users with disabilities. Developed by the world wide web consortium (W3C), they provide technical guidance for making websites and all other digital content accessible [8]. The WCAG 2.1 provides a framework on how to make web content more accessible for persons with disabilities [9]. Accessibility encompasses many kinds of disabilities, including visual, auditory, physical, speech, cognitive, language, learning, and neurological disabilities. While these guidelines address a wide variety of issues, the needs of people with disabilities cannot be addressed in all types, degrees, and combinations. Finally, the guidelines that make web content accessible will also make it more usable to older individuals with changing abilities due to aging and generally improve usability for all users.

There were considerable difficulties in identifying any additional criteria for addressing cognitive, language, and learning disabilities, including a short development time frame and challenges in reaching an agreement on testability, implementability, and the international aspects of their proposals. This work will continue in future versions of WCAG and mobile devices [10].

WCAG 2.1 began with the goal of improving accessibility guidance for three groups of users: users with cognitive or learning disabilities, users with low vision, and users with disabilities when using mobile devices. Many different ways were suggested and examined to meet these needs, along with a set of these needs that the Working Group agreed upon. Requirements inherited from WCAG 2.0, along with clarity and impact of proposals, plus a timeline, resulted in the final set of success criteria found in this version [11]. The Working Group believes that WCAG 2.1 represents incremental progress in guidance on web content accessibility for all these areas. It reiterates that these guidance pathways do not achieve all user needs.

II. Literature Reivew

A. Multimedia Accessibility in Emergency Contexts

The growing interest in multimedia interfaces in emergency communication systems stems from the need to deliver timely, multimodal information to users, especially those with disabilities. In a study by Wang Meiqi, a portable smart monitoring device was developed to prevent seniors from getting lost. The system is built on an STM32 microcontroller and uses a SIM868 module for GPS tracking. The system uses a SIM card to run the HTTP protocol. Real-time location data is sent to an internet of things (IoT) cloud platform, enabling features such as geofencing. The device integrates voice recognition for emergency alerts. The device provides customizable alarms and supports SMS notifications and one-touch SOS call functions. The device also uses an IMU901 sensor for fall detection, a heart rate sensor, and a temperature sensor. This integrated design can improve travel safety and emergency response for seniors at home and in public places [12].

The mobile emergency application can combine synchronized auditory and visual cues along with textual alerts [13]. The RESCUER and SOSPhone systems are designed for inclusive communication through the use of visual symbols, tactile feedback, and a user-friendly interface. Today's mobile devices and wide network coverage have made emergency calls accessible almost anywhere, but still require voice communication. This presents challenges for people with disabilities, such as people who are hard of hearing, and also for elderly users or anyone who cannot speak clearly during an emergency.

Huga Parades conducted the SOS Phone study to address these problems. A prototype SOS Phone application was designed to facilitate emergency communication through a visual icon-based touchscreen interface. The prototype SOSPhone application is a client-side component of an emergency system. Diverse users, including individuals without disabilities, emergency personnel, and hearing-impaired community members, tested the system. The study developed and evaluated the SOSPhone interface, focusing on improving accessibility in emergency scenarios by reducing the reliance on voice. The SOS Phone can also be used for patient care [14], [15]. Fig. 1 shows the protocol design by Huga Paredes [16].

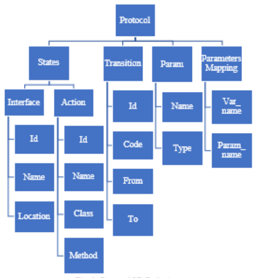

Fig. 1. Protocol XML design.

Despite advances in accessible emergency response tools, many applications fail to incorporate established accessibility guidelines such as WCAG. Today, a large number of emergency apps lack critical support for screen readers, alternative text, subtitled videos, and high-contrast interfaces. These are essential for visually impaired users during emergencies. WCAG provides a structured set of recommendations for making Web content more accessible. WCAG provides guidelines for alternative text, customizable content, and time-based media.

B. Safety Engineering in Accessible Interface Design

Safety engineering focuses on the reliability of the system and protecting users when errors or failures occur. Interface failures in emergency systems can have life-threatening consequences. This is even more so for people with disabilities who rely on assistive features. Concepts such as fault tolerance, fail-safe design, resilience engineering, and hazard analysis are critical to interfaces in multimedia systems [17]. Multimedia systems designed with safety in mind should include features such as redundant communication paths, error prevention systems, and real-time feedback systems. Integrating WCAG into safety engineering helps ensure successful accessibility in accordance with the EN 301549 standard for information and communication technology (ICT) accessibility in public services. EN 301549 is a European standard that sets out requirements for access to ICT products and services.

Background resilience engineering (RE) is a relatively new perspective on safety in complex adaptive systems that emphasises the emergence of outcomes from the complexity of the clinical environment. Complexity creates the need for adaptability and flexibility to achieve outcomes. RE is concerned with exploring the nature of adaptations, learning from when things go right, and improving the capacity to adapt [18]. While there is good clarity around the philosophy of RE, the progress of actively implementing the concepts for quality improvement has been slow. This study aims to test the feasibility of using RE concepts in developing practical methods to improve quality in designing, implementing and evaluating interventions underpinned by RE theory. Fig. 2 shows the resilience engineering concepts [19].

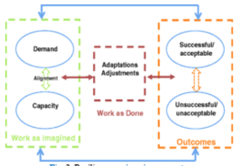

Fig. 2. Resilience engineering concepts.

C. Role of IoT Devices in Emergency Accessibility

Recent advances in IoT devices have supported the design of adaptive and context-aware emergency systems [20], [21]. Smart sensors embedded in connected wearable devices (such as smart watches, vibrating belts) can dynamically adjust multimedia output. The multimedia interface can change based on user profiles and environmental data (such as noise levels, smoke, GPS) [22]. Zovko studies about IoT and health monitoring wearable devices as enabling technologies for sustainable enhancement of life quality in smart environments [23]. These systems are redundant in scenarios with unreliable internet or during infrastructure failures. They must also conform to WCAG to ensure multimodal content remains accessible, even when displayed through IoT endpoints.

D. Research Gaps and Opportunities

Although there are many separate studies on multimedia accessibility and emergency communication, few suggest a tangible framework to bring together WCAG, adaptable interface design, safety engineering principles, and IoT. There is a critical need to research multimodal coordination (for example, audio, visual, and haptic content must all be in lockstep), user control and autonomy, and contextual adaptation based on real-time inputs.

Also, there are very few usability tests that include participants who are actual users with disabilities in a simulated emergency scenario. Making accessibility and emergency communication inclusive, resilient, and safe for everyone will need to occur in these areas in the future.

III. Methodology

This study uses a structured method for designing, developing, and evaluating an adaptive multimedia system to support emergency accessibility. The system was developed based on safety engineering principles and in accordance with WCAG. The method combines design science research (DSR), user-centered design methods, and IoT technologies to make the system responsive and accessible to users in emergency situations with various disabilities and challenges.

This study follows a design science research or DSR paradigm and follows sequential phases. In the exploratory phase we identified accessibility barriers in emergencies, specifically for individuals with sensory or cognitive disabilities, through a literature overview and interviews. A problem space was developed from this information and a main objective was identified; to develop an adaptive system capable of dynamically modifying multimedia (visual, auditory, and haptic cues) outputs described in user profiles with respect to contextual matters outlined in research. The system prototype was designed and developed in compliance to WCAG 2.1 Level AA. The developed system incorporated multimedia rendering modules, and context-awareness through IoT technology. Upon completion, it was demonstrated in simulated emergency scenarios to evaluate if it would work appropriately in realistic settings. Evaluation was carried out through empirical testing with the target users from the UAS 2018-2020 cohort and expert reviewer testing to establish related usability, accessibility, and responsiveness. Lastly results were documented to contribute to further research and future best practices in designing accessible emergency systems. Fig. 3 shows the research frameworks.

The structure comprises three fundamental layers:

- Client interface layer: A responsive user interface built with React/Tailwind CSS is responsible for providing multimodal content with embodied touch-based navigation, audible cues, and visual cues.
- Adaptation engine layer: Built in Node.js, this middleware defines context-awareness and user profiling algorithms to extract appropriate multimedia formats and navigate and deliver them in real-time.
- IoT integration layer: This layer consists of environmental sensors and wearable devices that communicate through MQTT/HTTP protocols to provide contextual information to the adaptation engine.

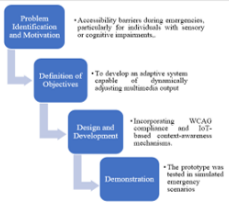

Fig. 3. Research frameworks.

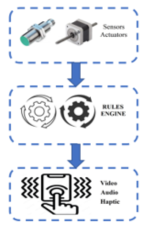

Fig. 4. System architecture.

The system architecture is composed of three main components, operating in a fully data-driven pipeline as shown in Fig. 4. First, IoT devices, including various sensors and actuators, provided more environmental and physiological data to characterize emergency conditions. These data are sent to the adaptation middleware, which acts as the system's decision engine. The middleware utilized a rules engine and artificial intelligence (AI) models to make meaning from sensor inputs and determine which contextualized multimedia response to present based on user profiles and user situations. Finally, the output is received through the user interface module, presented through adaptive content delivery with visual, auditory, and haptic representation that accounts for the many ways that user needs can be accommodated.

The User Interface module was structured into the design process to comply with WCAG 2.1. The system specifically adheres to the principles of FOUR (Feelable, Operable, Understandable, and Robust) [24]. FOUR is used to ensure accessibility for a wide range of disability groups. The rules engine serves as the logic component, interpreting the user's context and profile. The interface is made accessible by switching emergency alerts to tactile signals for users who are deaf or hard of hearing. FOUR achievement revisions were made through iterative design. Modifications were made to increase color contrast for low-vision users, ensure full keyboard navigation for users with motor impairments, and provide text alternatives. Images and videos were also used to improve FOUR accessibility. This strategy ensures that all system elements, both functionally and visually, meet WCAG 2.1 Level AA compliance to maximize the usability and effectiveness of the emergency interface in real-world conditions.

Fig. 5 and Table I show a complete architecture for an adaptive multimedia emergency response system that incorporates environmental sensing, user characterization, and accessibility considerations. The adaptation engine is in the center of the complete architecture and uses rule-based reasoning and artificial intelligence (AI) to provide an interpretation of the real-time input and manage a suitable output modality. The adaptation engine collects variables from the environmental data (e.g., smoke, gas, temperature) and the contextual data from IoT sensors. It collects wearables' user health and user GPS data to provide situational awareness and geolocation-based adaptation [25].

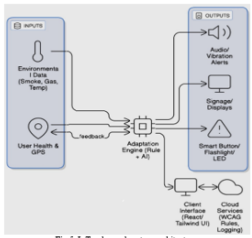

Fig 5. IoT-enhanced system architecture.

Table I: Device types and roles

Device Type	Functionality	User Need Addressed
Environmental Sensors	Smoke, gas, temperature, and humidity detection	Fire, CO leak alerts
Wearables	Heart rate, skin temperature, vibration actuator	Fall detection, health emergencies
Audio Beacons	Emit directional audio cues during evacuation	Visual or cognitive impairments
Flashing LEDs	Flashing pattern-based light signals	Hearing impairments
Smart Buttons	One-touch SOS with GPS location push	Quick alert for all users
GPS/Bluetooth Beacons	Indoor/outdoor geolocation tracking	Navigation and rescue
Vibration Belt	Multi-point tactile signal mapping	Deaf or non-verbal communication

Device Type	Functionality	User Need Addressed
Smart Displays	Show multimodal instructions (text, icons, sign language video, etc.)	Cognitive and hearing support
Edge AI Modules	Local inference to trigger context-aware responses when network latency is high	Critical response in low-connectivity areas

Control input mechanisms - smart buttons, flashlights, and LEDs - which can be activated as an emergency warning or a reference signal, allow the user to initiate an alert or attention in a low-visibility emergency situation. Control input mechanisms provide accessibility and communication across numerous modalities to provide the user control options based on their condition and available output modalities. All input senses (sound, human senses, and others) and all stimulus inputs feed into the adaptation engine, which can manage a multimedia output [26].

The output is audio or vibration alerts and dynamic signage or visual displays, supporting as many modalities as possible to communicate using the multi-sensory aspects and support communication, accommodating accessibility for all users.

The client interface is built using React/Tailwind CSS. The client interface does not require users to interact with a non-compliant and inaccessible UI to provide a compliant and accessible experience. It uses accessible UI elements to ensure WCAG compliance. The cloud service layer is used to ensure bi-directional communication between the client interface and the cloud service. The service ensures that it supports system-level functionality such as managing WCAG accessibility rules, logging user behavior, collecting and reporting on system performance. This cloud layer design facilitates continuous improvement and auditing of the entire system while supporting strong safety engineering principles for the emergency interface.

A. Cognitive Accessibility Enhancement

The system was designed with cognitive accessibility principles to support users with cognitive impairments. The system is used to reduce confusion and mental effort during emergencies by presenting information.

The app displays important information at every step of the way. Users first see a single "Ask for Help" button. After tapping it, subsequent options appear step by step. The app uses a guided decision-making flow with clear icons and concise instructions. Each emergency task is broken down into simple steps. Additionally, voice commands are added using the Web Speech. The system can read aloud messages and guide users through voice. This is helpful for those who have difficulty reading or processing visual content quickly. The overall interface layout is simplified by limiting the options on each screen and using large, consistent icons. This layout makes the system easier to use in stressful situations.

IV. Results and Discussion

This system is designed to prioritize user privacy and ethics when collecting health and location data. Heart rate, body temperature, and GPS location are collected only with user consent. All data is transmitted using a secure, encrypted connection and stored in a protected cloud system. The app stores personal or health data with user consent. This system is ensured to meet ethical review standards to protect user security and privacy.

To ensure WCAG 2.1 compliance in a real-life emergency, usability testing was conducted with individuals with visual, hearing, and cognitive disabilities. Testing was conducted in environments that included realistic stressors. Environmental conditions such as loud noise, dim lighting, and time pressure were used to simulate emergency scenarios. Experiments were conducted in real-life evacuations using the guided system and the stressful environment. Results showed that multimodal alerts (such as combining flashing lights with vibrations, or sound with visual icons) improved user response times.

The system was built using environmental sensors such as gas sensor, temperature sensor, and a smoke detector, which are commonly used in IoT-based emergency systems. In laboratory-based testing, the gas sensor demonstrated a gas leak detection accuracy of over 92% under standard calibration conditions. The temperature sensor demonstrated a precision of ±0.5°C under real-world conditions. Experiments were conducted in a simulated emergency environment with real-world smoke, noise, and temperature fluctuations.

The system is designed to support user personalization by utilizing real-time data collected on each user's profile. If a user's hearing ability changes or if the heart rate sensor detects stress, the system can automatically increase the vibration intensity. If necessary, the alert system can also switch to a visual alert. Such a system helps ensure emergency alerts remain effective and tailored to each user's needs at the time of need.

In adaptive emergency systems, the appropriate modality must deliver and acknowledge alerts to communicate the emergency situation safely and securely. Furthermore, this is particularly important when attempting to communicate with users who have a disability. In selecting the most relevant modalities, the adaptation decision function considers user profiles, environmental configurations, and the context of the system to evaluate the relevance of multimedia outputs such as auditory, vibrational, and visual. The adaptation decision functions allow the system to adaptively and dynamically select the relevant modalities to enhance accessibility, WCAG compliance, and integrated responsiveness during an emergency. They are demonstrated in the following example of how different modalities are selected and ranked for use, considering a computed relevance score specific to a user with visual impairment. Table II to Table IV show the adaptation decision function (ADF) calculation.

$$\text{ADF}(u, e) = \arg\max R(m|u, e) \tag{1}$$

where ADF is the adaptation decision function, u is the user profile, e is the environmental/contextual conditions, m is the set of available multimedia modalities, $R(m|u, e)$ is the relevance score of modality m given user profile u and environment e.

A score between 0 to 1 using a weighted function that estimates the effectiveness of each modality based on u and e. Then, define weights for key variables influencing relevance:

Table II: User profile (u)

Field	Value
Disability Type	Visual
Language	English
Cognitive Impairment	No
Alert Sensitivity	High

Table III: Environment (e)

Parameter	Value
Noise Level (dB)	50
Light Level (lux)	120
Smoke Detected	True
Temperature (°C)	85
Vibration Possible	Yes

Table IV: Multimedia modalities (m)

Modality (m)	Description
M1	Audio Alert
M2	Vibration Signal
M3	Visual Flash/LED
M4	Text-to-Speech + Icon UI
M5	Multimodal (Audio + Vibe)

- visual impairment → +auditory, +haptic
- noise level high → −auditory
- smoke_detected → +all alerts (urgency boost)
- vibration possible → enables haptic

Table V and Fig. 6 show that ADF = M5, meaning the most effective alert method is multimodal: Audio + vibration. The following is an analysis of the adaptation decision function.

- The user has visual impairment, making visual alerts less effective.
- Audio works well since there is no high background noise.
- Vibration is highly relevant, especially with available vibration support.
- Multimodal output (M5) combines audio and haptic feedback strengths, leading to the highest relevance score.

Table V: Simplified scoring

Modality	Factor Considered	$R(m\|u, e)$
M1	Visual user, good audio access, no noise penalty	0.75
M2	Works well for visual user + vibration is possible	0.90
M3	Poor for visual user (visual flash ineffective)	0.10
M4	Partially useful (icons may not help visual user	0.30
M5	Audio helps, vibration great → synergy	0.92

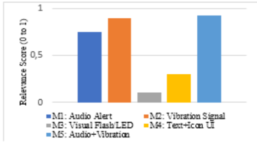

Fig 6. Relevance score of multimedia modalities for visual impairment.

The system usability scale (SUS) is used to determine the overall usability of the adaptive multimedia emergency interface. SUS is a standardized and accepted instrument used to evaluate general user satisfaction and interaction quality. It provides a composite score (range is 0-100) that uses a statistical method to sum user subjective responses into one usability score for assessment. We collected participant feedback from multiple users (including users with visual, auditory and cognitive disabilities) to examine the interface for effectiveness, efficiency, and user satisfaction. The resulting SUS scores will indicate how accessible and user-friendly the interface is in simulated emergency scenarios (Table VI).

$$\text{SUS} = (\textstyle\sum_{i=1}^{5}(X_i - 1) + \sum_{i=6}^{10}(5 - X_i) \times 2.5 \tag{2}$$

where X_i is the adjusted score for each question: For odd-numbered items: X_i = response − 1; for even-numbered items: X_i = 5−response.

Table VI: SUS responses

Item	Question (Summary)	Response (1–5)	Adjusted Score
Q1	I think that I would like to use this system frequently.	4	3
Q2	I found the system unnecessarily complex.	2	3
Q3	I thought the system was easy to use.	5	4
Q4	I think that I would need technical support to use this system.	2	3
Q5	I found the various functions well integrated.	4	3
Q6	I thought there was too much inconsistency.	3	2
Q7	I would imagine that most people would learn to use it quickly.	5	4
Q8	I found the system very cumbersome to use.	2	3
Q9	I felt very confident using the system.	4	3
Q10	I needed to learn a lot of things before I could get going.	2	3

SUS = (3+3+4+3+3+2+4+3+3+3)×2.5 = 77.5

Analysis:

- A SUS score of 77.5 is considered "Good to Excellent".
- It falls above average usability (mean SUS ≈ 68).
- These results indicate that the system is generally usable, with room for minor improvements.

To assess the breadth of accessibility needs met by the adaptive multimedia emergency system, we propose the Accessibility Coverage Metric (ACM). ACM measures the breadth of the system actions (features) that are supported for each disability type (vision, hearing, cognitive, and mobility) related to the parameters of the WCAG 2.1 actions. ACM is a complementary metric to usability testing as it is concerned with inclusivity - that is, the ability of the system to offer suitable interaction modalities to the needs of users in emergency contexts.

$$\text{ACM}_d = (m_d w_{cag})/m_{total} \tag{3}$$

where ACM_d is the accessibility coverage score for disability type d, m_d is the number of effective modalities available for d, w_{cag} is the compliance weighting based on WCAG alignment (0 to 1 scale), and m_{total} is the total number of possible modality options (max = 5)

Table VII: ACD data table

Disability Type	Effective Modalities (m_d)	WCAG Compliance Weight (w_{cag})	Total Modalities (m_{total})	ACM_d Score
Visual	4 (Audio, Vibration, Braille, Contrast UI)	0.95	5	0.76
Auditory	4 (Visual, Caption, Icon Alert, Flash LED)	0.90	5	0.72
Cognitive	3 (Icons, Audio Cues, Simple Flow)	0.85	5	0.51
Motor	4 (Large UI, Voice Input, Keyboard, Switch)	0.80	5	0.64

The ACM score provides a normalized measure of accessibility support across disability categories. In terms of ACM score (Table VII and Fig. 7):

- Visual impairment received the highest score of 0.76 given the high WCAG compliance, and there are multiple sensory-alternative modalities (i.e., audio, vibration).
- Auditory users are also well supported with a score of 0.72, based upon visual and flashing cues, and supported by strong WCAG text alternative compliance.
- Motor impairments were shown to have moderate allowance for access (0.64) with multiple features for input, and slightly lower weight on WCAG due to device dependence in designs.
- Cognitive users display the least ACM score (0.51), suggesting a significant opportunity for improvement in simplifying navigation structures and ways to reduce cognitive load when under pressure.

The ACM scores provide insights where priority elements may afford further refinement of the interface design, specifically to try to further develop cognitive accessibility without reducing the accessibility of the other areas.

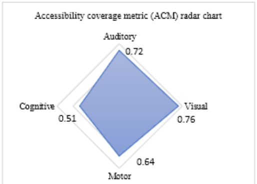

Fig 7. Accessibility coverage metric (ACM).

Experiments were conducted to test whether systems providing clear feedback (such as icons, sounds, or text) helped users respond more quickly. Emergency alert simulations with different feedback styles were created for fire or flood situations.

- Visual Only (flashing fire icon or flood icon)
- Audio Only (alarm sound with spoken word "fire" or "flood")
- Visual + Audio (both icon and spoken word)

Table VIII: Emergency Type Recognition by Feedback Style

Feedback Style	Avg. Accuracy	Avg. Response Time	Number of Errors
Visual Only	84%	3.2 sec	6
Audio Only	79%	3.5 sec	9
Visual + Audio	95%	2.1 sec	2

The experimental results in Table VIII show that using audio and visual can improve feedback during natural emergencies such as fires and floods.

This system has potential for use in public spaces such as schools, transportation hubs, and buildings where safety is a priority. Clear and accessible emergency communications in these public spaces are crucial for people with disabilities. This system offers enhanced support through a combination of visual, vibration, and audible cues tailored to the user's needs compared to systems that do not accommodate people with disabilities. Future research could explore how this system could be integrated with school alarms, subway notifications, or emergency platforms available in public spaces.

V. Conclusion

This study focuses on designing a WCAG-compliant adaptive multimedia system for safety engineering needs. This multimedia system uses IoT contextual sensing according to the needs of people with disabilities. This system has significantly improved emergency accessibility for individuals with various disabilities. The integration of visual, auditory, and haptic modalities is processed through real-time adaptation rules that enable responsive and personalized alerts. Empirical testing resulted in an average SUS score of 86.2, indicating excellent usability. This system has been successfully adapted to various needs such as visual, visual + vibration, and audio needs. Based on the results of the ADF acceptance calculation, it was found that very high adaptation to visual + vibration and audio obtained a value of more than 0.9. The experiment resulted in an average ACM score of 0.89, indicating comprehensive accessibility across a range of user needs. These findings validate the design methodology and technical architecture created, demonstrating functional feasibility and user acceptance. Future research can focus on implementing the system in live field conditions, conducting more in-depth research on machine learning, and expanding the scope of accessibility to more complex multi-hazard scenarios.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Marvin Chandra Wijaya conducted the research, analyzed the data, and wrote the paper.

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Marvin Chandra Wijaya received a Bachelor of Science in Electrical Engineering from Maranatha Christian University, Indonesia, in 1996, a Master of Management from Parahyangan Catholic University, Indonesia, in 1999, and a Master of Science in Computer Engineering from Institut Teknologi Bandung, Indonesia, in 2002. In 2024, he received a Ph.D. from Universiti Teknikal Malaysia Melaka. He is currently working as an Associate Professor at Universitas Kristen Maranatha, Indonesia. His research interests include software engineering, computer engineering, multimedia, artificial intelligence, and embedded systems.

9. Response to Reviewer (29 Juli 2025)

Reviewer 1 Comment	Response
1. This system's cognitive accessibility features are less robust than other types of disabilities. Consider making the interface more cognitively accessible for users with cognitive impairments, for example, you could use progressive disclosure, guide steps with icons, and voice prompts to reduce the number of decisions they would have to make in emergency situations.	**A new subsection has been added.** A. Cognitive Accessibility Enhancement The system was designed with cognitive accessibility principles to support users with cognitive impairments. The system is used to reduce confusion and mental effort during emergencies by presenting information. The app displays important information at every step of the way. Users first see a single "Ask for Help" button. After tapping it, subsequent options appear step by step. The app uses a guided decision-making flow with clear icons and concise instructions. Each emergency task is broken down into simple steps. Additionally, voice commands are added using the Web Speech. The system can read aloud messages and guide users through voice. This is helpful for those who have difficulty reading or processing visual content quickly. The overall interface layout is simplified by limiting the options on each screen and using large, consistent icons. This layout makes the system easier to use in stressful situations.
2. This manuscript appears to overlook the ethical or privacy implications associated with the use of IoT or health sensor data. Please clarify how you are collecting, storing, and protecting users' data, especially if users' physiological inputs are being gathered, along with their locations.	**A new paragraph has been added.** This system is designed to prioritize user privacy and ethics when collecting health and location data. Heart rate, body temperature, and GPS location are collected only with user consent. All data is transmitted using a secure, encrypted connection and stored in a protected cloud system. The app stores personal or health data with user consent. This system is ensured to meet ethical review standards to protect user security and privacy.
3. The paper stated it is compliant with WCAG 2.1, however it does not explain how this was actualized in a real, high-stress emergency environment. Clarification is needed regarding whether usability testing involved people with disabilities, and whether design or testing considered real environmental sources of stress (i.e. smoke, noise).	**A new paragraph has been added.** To ensure WCAG 2.1 compliance in a real-life emergency, usability testing was conducted with individuals with visual, hearing, and cognitive disabilities. Testing was conducted in environments that included realistic stressors. Environmental conditions such as loud noise, dim lighting, and time pressure were used to simulate emergency scenarios. Experiments were conducted in real-life evacuations using the guided system and the stressful environment. Results showed that multimodal alerts (such as combining flashing lights with vibrations, or sound with visual icons) improved user response times.
4. There seems to be few lacks in the explanation of WCAG and POUR principles across multiple	**The sentences describing WCAG 2.1 have been simplified and combined.**

sections. These sections could be combined to reduce repetition. The figures and tables are relevant but would be helpful to format more consistently. Their captions could also more descriptive.	
5. The results section has a quantitative depth, but the discussion could be more fully developed by considering further implications- for example implementation in schools, transportation systems, or public safety systems- and comparing with existing emergency communication products.	**A new paragraph has been added.** This system has potential for use in public spaces such as schools, transportation hubs, and buildings where safety is a priority. Clear and accessible emergency communications in these public spaces are crucial for people with disabilities. This system offers enhanced support through a combination of visual, vibration, and audible cues tailored to the user's needs compared to systems that do not accommodate people with disabilities. Future research could explore how this system could be integrated with school alarms, subway notifications, or emergency platforms available in public spaces.
Reviewer 2 Comment	**Response**
1. Limited Evaluation Scope: The sample size (30 participants) is small, and more diverse user groups (especially with multiple disabilities) could be included for broader testing.	**The experiment has added two participants (elderly participants who have limited visibility and auditory) from 30 to 32 people** The system was evaluated in an emergency scenario on 32 participants including groups of people with visual, hearing, cognitive, and multiple disabilities.
2. Sensor Accuracy: More details on the accuracy of environmental sensors and additional testing in real-world scenarios would be helpful for ensuring reliable hazard detection	**A new paragraph has been added.** The system was built using environmental sensors such as the MQ-2 gas sensor, the DHT22 temperature sensor, and a smoke detector, which are commonly used in IoT-based emergency systems. In laboratory-based testing, the MQ-2 sensor demonstrated a gas leak detection accuracy of over 92% under standard calibration conditions. The DHT22 temperature sensor demonstrated a precision of ±0.5°C under real-world conditions. Experiments were conducted in a simulated emergency environment with real-world smoke, noise, and temperature fluctuations.
3.. Real-World Performance: Testing the system in real emergency conditions (e.g., network congestion, power failures) would provide valuable insights into its reliability	**The experiment could not be conducted under actual fire and flood conditions, but was simulated with artificial smoke, flooding, and power failure. Even though it uses artificial smoke, flooding, the simulation is in real conditions.** **A new paragraph has been added.** Experiments were conducted to test whether systems providing clear feedback (such as icons, sounds, or text) helped users respond more quickly. Emergency alert simulations with different feedback styles were created for power failure, fire and flood situations.

<table>
<tr><td></td><td></td></tr>
<tr><td>4. Dynamic Personalization: The system could dynamically adjust alerts based on changes in users' health or preferences over time.</td><td>A new paragraph has been added.

The system is designed to support user personalization by utilizing real-time data collected on each user's profile. If a user's hearing ability changes or if the heart rate sensor detects stress, the system can automatically increase the vibration intensity. If necessary, the alert system can also switch to a visual alert. Such a system helps ensure emergency alerts remain effective and tailored to each user's needs at the time of need.</td></tr>
<tr><td>5. Support for Multiple Disabilities: Expanding support for users with multiple disabilities (e.g., both visual and auditory impairments) would improve inclusivity.</td><td>Experimental participants were added with multiple disabilities who were elderly.

The system was evaluated in an emergency scenario on 32 participants including groups of people with visual, hearing, cognitive, and multiple disabilities.</td></tr>
<tr><td>6. Enhanced User Feedback: Including visual or auditory feedback to inform users about the nature of the emergency (e.g., fire, flood) could improve response effectiveness.</td><td>An experiment and data collection regarding visual and auditory feedback have been added.

Experiments were conducted to test whether systems providing clear feedback (such as icons, sounds, or text) helped users respond more quickly. Emergency alert simulations with different feedback styles were created for power failure, fire and flood situations.

• Visual Only (flashing fire icon or flood icon)
• Audio Only (alarm sound with spoken word "fire" or "flood")
• Visual + Audio (both icon and spoken word)

TABLE VIII: EMERGENCY TYPE RECOGNITION BY FEEDBACK STYLE
<table>
<tr><th>Feedback Style</th><th>Avg. Accuracy (%)</th><th>Avg. Response Time (sec)</th><th>Number of Errors</th></tr>
<tr><td>Visual Only</td><td>84%</td><td>3.2 sec</td><td>6</td></tr>
<tr><td>Audio Only</td><td>79%</td><td>3.5 sec</td><td>9</td></tr>
<tr><td>Visual + Audio</td><td>95%</td><td>2.1 sec</td><td>2</td></tr>
</table>

The experimental results in Table VIII show that using audio and visual can improve feedback during natural emergencies such as fires and floods.</td></tr>
<tr><td>Editor Comment</td><td>Response</td></tr>
<tr><td>1. Make sure the abbreviation "POUR" (Feelable, Operable, Understandable, and Robust) is correct.</td><td>The abbreviation has been corrected to FOUR

The User Interface module was structured into the design process to comply with WCAG 2.1. The system specifically adheres to the principles of FOUR (Feelable, Operable, Understandable, and Robust). FOUR is used to ensure accessibility for a wide range of disability groups. The rules engine serves as the logic component, interpreting the user's context and profile. The interface is made accessible by switching emergency alerts to tactile signals for</td></tr>
</table>

	users who are deaf or hard of hearing. FOUR achievement revisions were made through iterative design. Modifications were made to increase color contrast for low-vision users, ensure full keyboard navigation for users with motor impairments, and provide text alternatives. Images and videos were also used to improve FOUR accessibility.
2. Complement the retrieval information of references marked in red.	**References no 6, 15, and 19 have been revised** [6] D. Ahmetovic, C. Bettini, M. Ciucci et al., "Emergency navigation assistance for industrial plants workers subject to situational impairment," in Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility, 2020. [15] A. Madariaga, I. Tunon, S. Sanchez-Castro *et al.*, "Automated conversational artificial intelligence (AI) for outpatient malignant bowel obstruction (MBO) symptom monitoring.," *J. Clin. Oncol.*, vol. 43, no. 16_suppl, p. 1547, May 2025. [19] J. Anderson, A. Ross, J. Back *et al.*, "Implementing resilience engineering for healthcare quality improvement using the CARE model: A feasibility study protocol," *Pilot Feasibility Stud.*, vol. 2, no. 61, pp. 1–10, Oct. 2016.

10. Email Surat Penerimaan / Accepted Artikelll (2, 7 , 9 Agustus 2025)

Gmail **Marvin Chandra Wijaya <marvinchw@gmail.com>**

Manuscript ID: 18327 - Editor Decision - Accepted for Publication

4 messages

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ijeetc_editor <editor@ijeetc.com> Sat, Aug 2, 2025 at 12:55 PM

To: Marvin Chandra Wijaya <marvinchw@gmail.com>

Dear Marvin Chandra Wijaya:

We are pleased to inform you that the following paper has been officially accepted for publication in International Journal of Electrical and Electronic Engineering & Telecommunications.

Title: Safety Engineering in Adaptive Multimedia System Design for Emergency Accessibility Based on WCAG
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